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FOR THE
30-MJ BONNEVILLE POWER ADMINISTRATION SMES COIL*

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Summary

The 30-MJ energy storage coil for the Bonneville Power Administration requires a low-loss, cryostable conductor that is able to carry 4.9 kA in a field of 2.8 T and will maintain its properties over 10^8 partial discharge cycles. The multi-level cable which satisfies these requirements has been extensively tested at various stages in its development and in its final form. Tests have been performed to determine the effect of manufacturing options on ac losses, low temperature electrical resistivity, stability, and fatigue resistance of the insulated conductor. This paper will concentrate on the stability and fatigue tests which have not previously been reported.

Introduction

The final set of tests, undertaken to insure that the conductor for the 30-MJ System Stabilizing Magnet for the Bonneville Power Administration (BPA) will perform as specified, is described. Design requirements for the conductor are set by the coil performance, Table I. The conductor configuration is shown in Fig. 1 and specified in Table II. Previous publications have discussed the impact of fabrication options on conductor performance[1] and measurement of the ac loss characteristics of this configuration.[2] Described here are stability tests which show that the conductor, as mounted in the coil, will be cryostable at a current of 7 kA, well above the required 5 kA. Further tests, also described, show that the conductor, and particularly the Mylar tape electrical insulation, will withstand the required number of load cycles. Information is also presented on acceptance testing for copper and superconductor.

TABLE I
DESIGN PARAMETERS OF THE 30-MJ SYSTEM
STABILIZING SMES UNIT

Maximum power capability, MW	10
Operating frequency, Hz	0.35
Maximum stored energy, MJ	30.0
Interchange energy, MJ	9.1
Coil current at full charge, kA	4.9
Maximum coil terminal voltage, kV	2.16
Coil operating temperature, K	4.5
Coil lifetime, cycles	$>10^8$
Heat load at 4.5 K, W	<150
Mean coil diameter, m	3.0

*Work performed under the auspices of the U. S. Dept. of Energy.

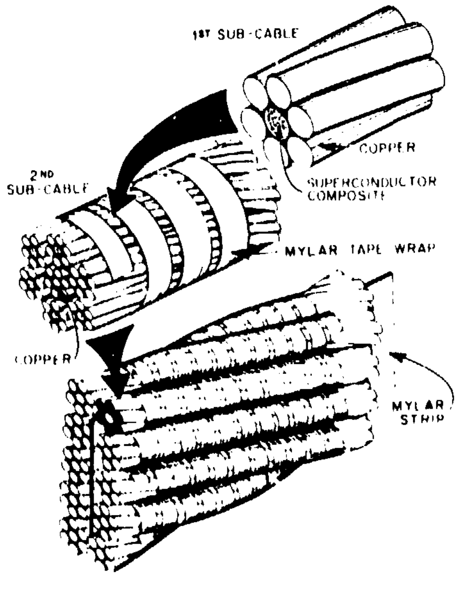

Fig. 1. Low-loss cryostable cable for 30-MJ coil.

TABLE II
CONDUCTOR SPECIFICATIONS FOR 30-MJ COIL

A.	Superconductor Composite Core	
	Area of NbTi, mm^2	4.85×10^{-2}
	Filament diameter, μm	6.5
	Number of filaments	1464
	Strand diameter, mm	0.511
	Cu to NbTi ratio	2.94:1
	Twist pitch, mm	5.0
B.	First Subcable	
	(Six copper wires cabled about one core)	
	Uncompacted diameter, mm	1.52
	Compacted diameter, mm	1.37
	Overall Cu to NbTi ratio	26.7:1
	Twist pitch, mm, and direction	13.5; L.H.
C.	Second Subcable	
	(Six first subcables around a stranded, insulated copper core)	
	Diameter, mm	4.11
	Twist pitch, mm, and direction	34.9; R.H.
	Insulation type	Mylar, adhesive
	Insulation size, mm	0.15 × 6.4
	Insulation pitch, mm, and direction	[illegible]; L.H.
D.	Finished Conductor	
	(Ten second subcables around a Mylar strip)	
	Strip dimension, mm	15 × 0.25
	Conductor dimension, mm	23.6 × 7.6
	Twist pitch, mm, and direction	200; L.H.

Quality Control and Acceptance Tests

To construct the coil we purchased 6.4×10^5 m of superconducting composite core from Magnetic Corporation of America. Specifications called for the wire to carry at least 110 A at 4.2 K and 3.0 T as measured at a sensitivity of 1×10^{-12} Ω-cm, which would cause the poorest piece of wire to operate at 80% of specification along the load line. The wire as received carried (125 ± 11) A under specified conditions, as measured on 64 random samples.

A compacted first subcable requires 5.04 times as much copper as composite core. Accordingly, we purchased 3.5×10^6 m of 0.511 mm PDOF copper wire. Wire as received and re-annealed had a RRR of 321 ± 25, as measured on 21 samples at 4.0 K. After compaction, the first subcable must be annealed at 325° C for 2 hr; a temperature of 300° C produces inadequate annealing and a temperature of 350° C will begin to damage the superconductor. As a QC measure, one sample from each annealing lot will be subjected to critical current and RRR tests for comparison with the initial values.

Stability Tests

Experiment

Preliminary experiments had indicated that relatively small gaps in an insulating wrap on a cable were very effective in permitting heat transfer to the liquid helium. Mylar strip, 0.25-in. wide, 0.005-in. thick, perforated with two staggered rows of 1/16-in. holes on 1/8-in. centers, appeared to provide sufficient ventilation while simultaneously preventing accidental contact between second subcables. Much of the data presented here were taken using such insulation. As a result of these measurements, it is felt that the advantage of perforated strip is not enough to overcome the large additional expense of perforation and the fabrication problems produced by the lack of adhesive on the strip. Therefore, additional runs, including that on the 5 kA conductor itself, were performed using unperforated, adhesive backed, 0.005-in. thick, 0.25-in. wide, Mylar tape.

Experiments and analysis have been previously described in detail.[3] In the majority of tests, the sample consisted of a 10-to-15 meter length of second subcable wound onto a cylindrical G-10 mandrel, as shown in Fig. 2. Except for the 15° angle which the second subcables make with the conductor axis in Fig. 1, the geometry of Fig. 2 closely simulated the heat transfer environment of the cables as they are mounted in the 30-MJ coil. The sample length was usually divided into several regions, each consisting of five turns around the mandrel and each utilizing a different insulation system. For instance, Fig. 2 shows a section of bare cable in the lowest region, a cable section insulated with perforated strip with 1-mm gaps in the central region, and a cable section insulated with butt-wrapped perforated strip in the upper region. A 1-cm length of cable on the third turn of each region was wrapped with an 8-Ω heater formed of metal film laminated between Kapton strips. Voltage taps, carefully dressed to avoid inductive pickup, were spaced along the cable one-or-two twist pitches apart.

Samples could be supplied with a current up to 3 kA in a field up to 6 T. Data for heater current, sample current, and voltage across six pairs of taps as functions of time were recorded using a PDP-11/34 computer and simultaneously, as a check, on a strip-chart recorder. These electrical measurements have an accuracy of 2% or 2 μV, whichever is greater. The primary quantity of interest was the recovery current, defined as the largest current for which a normal zone would recover when the heater power was removed. The heater was typically energized for 5 s at a power level approximately 10% larger than that required to form a measurable normal zone. Recovery currents are usually defined within ±25 A.

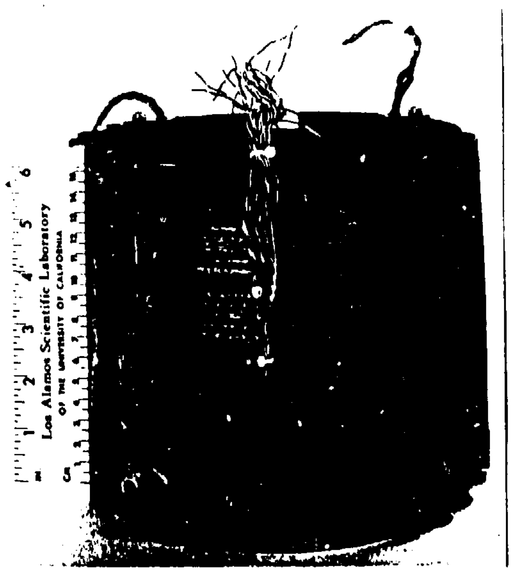

Fig. 2. Test assembly for second subcable in simulated 30-MJ geometry. Three support strips and a surrounding Mylar shell have been removed for clarity.

A number of anomalies previously noted[3] in experiments on cabled conductors were resolved by noting that our heater arrangement affects the six first subcables in a very unequal manner. Since, at a current below the recovery current, the length of a normal zone depends largely upon the heater input, the normal zones in the first subcables extend very different distances from the heater. The measured transverse electrical resistivity[2] is small enough to permit sufficient current sharing among the first subcables, but the corresponding thermal resistance is large enough to permit these unequal zones to persist. Thus, if all the voltage taps are not on the same first subcable, curious patterns of voltage versus heater power may appear, including an apparent left-right asymmetry with respect to the heater. Even with the present precaution of attaching all voltage taps to the same first subcable, the voltage patterns are not simple to interpret. For instance, we observe strong current transfer effects as individual first subcables carry, over short distances, currents well above or below the average value.

Finally, we occasionally find normal zones which neither propagate nor decay when the heater power is removed. Such zones are always centered on the heater, presumably because of the relatively poor heat transfer in this region, and display unusual values of voltage per unit length, indicating unbalanced currents. These zones may be very long in heavily insulated samples and may begin to form at a current considerably below the recovery current. Their existence seems to be associated with especially poor transverse electrical and thermal conductance caused by a combination of surface contamination, insufficient winding tension, and excessively long twist pitch. Above the recovery current, in all cases, the observed cable resistance is equal to that expected from an independent RRR measurement, a fact which verifies that a true propagating zone has been observed.

Results

Fig. 3 presents data on recovery current versus fractional coverage of perforated strip, for the sample geometry of Fig. 2, at three different fields. Fractional coverage is calculated using only the gap between successive turns of strip and does not include the 20% open area due to the perforations. The most striking feature of this data is the relatively small effect of what is, after all, a rather hefty layer of insulation. It should be noted that all recovery currents at 2.8 T are well above both the 30-MJ operating current of 490 A per second subcable and the critical current, 750 A at 1×10^{-12} Ω-cm. The points in Fig. 3 scatter more than would be expected from experimental statistics, due to unavoidable variation in insulation pitch and cable mounting among samples.

The same data are replotted in Fig. 4 as recovery heat flux, q_R, versus fractional coverage, where $q_R = I^2\rho/AP$. Here, I is the recovery current, ρ the measured resistivity, and A the copper area of the second subcable, ignoring the copper core which was disconnected so as not to carry current. For uniformity in presenting the data, P was taken as the perimeter of six first subcables, each treated as a round wire 1.37 mm in diameter. This, presumably, grossly overestimates the wetted perimeter and thus makes the absolute heat flux values small compared with those of other workers. Experimental scatter obscures any dependence of q_R on magnetic field; the data are consistent with a decrease of 10% in q_R between zero and 3 T observed by Wollan et al.[4] for bare wire as

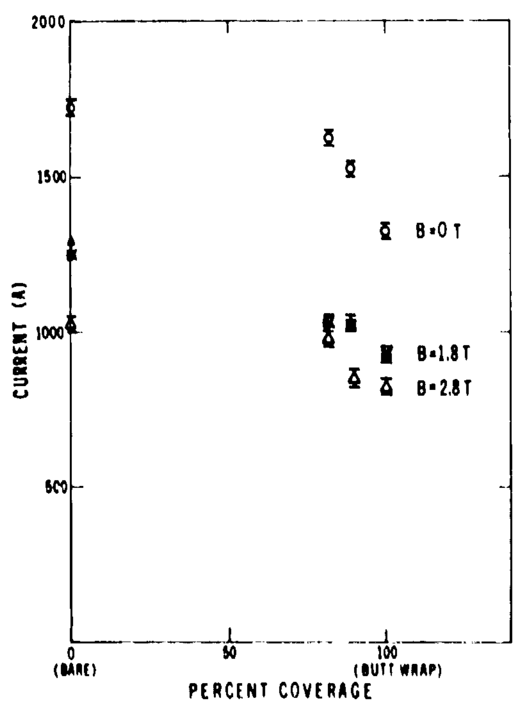

Fig. 3. Recovery current in second level cable vs. percentage of coverage with perforated strip. Simulated BPA geometry.

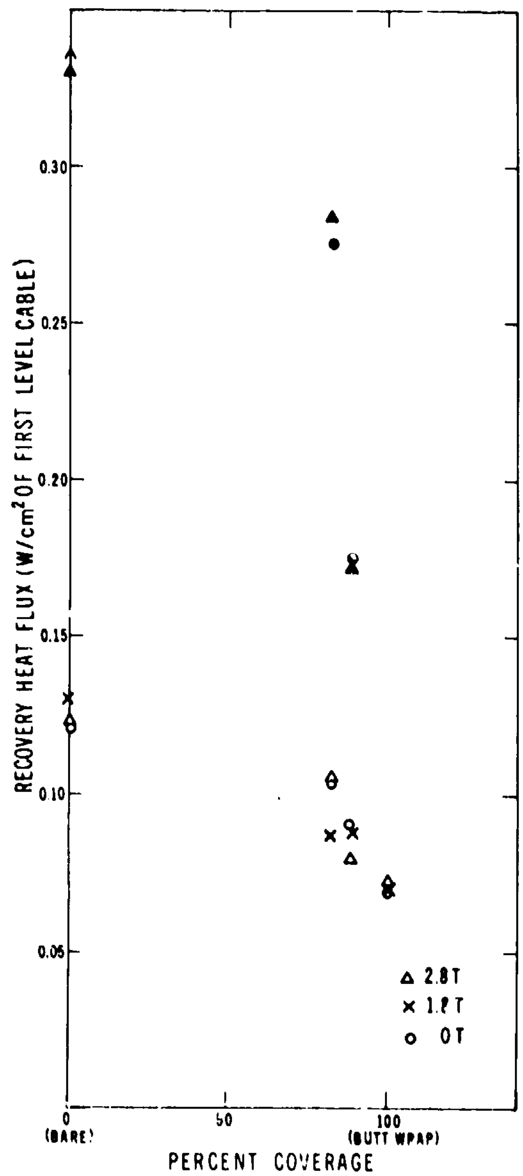

Fig. 4. Recovery heat flux per first level cable vs. percentage of coverage with perforated strip. Measured on second level cable. Open points – simulated BPA geometry; solid points – open geometry.

well as wire insulated with a thin layer of Omega or a thick wrapping of nylon roving.

Figure 4 also contains data taken on a length of insulated second subcable mounted in an "open geometry" that provided maximum helium access to the sample. In this case there is a dramatic decrease in q_R at coverages greater than about 80%. An extrapolation of the data leads to the conjecture that the recovery current with 100% coverage might be independent of support structure, as the data of Wollan et al. also indicate. Thus, the recovery heat flux is affected strongly by either insulation or support structure, but the effects are not additive.

Tests on 0.005-in. thick unperforated Mylar tape were run only at 88% coverage, that is, 0.040-in. gaps between turns of 0.25-in. wide tape. Results are summarized in Fig. 5 in which selected points from Fig. 4 are repeated for comparison. Experiments using the geometry of Fig. 2 were only sufficient to establish a lower bound for q_R, while experiments on the 5 kA conductor itself better served to establish q_R.

In a final test, a 7-m length of pre-production, 5-kA conductor, with the second subcables soldered together at the ends to form a bifilar sample, was wound in a single layer on a modified version of the G-10 mandrel and fitted with support teeth and insulating strips to match the actual heat transfer environment in the 30-MJ coil. It was possible to heat a single second subcable or all ten subcables simultaneously. The latter case should correspond more closely to the arrangement of Fig. 2, in which all five neighboring turns are driven normal when the zone propagates. When a single second subcable was heated, no normal zones were observed in neighboring strands until, at a current rather larger than the recovery current for the heated strand, the zones were able to propagate thru the solder joints between the second subcables. It is thus possible not only to drive a single strand normal in a cabled conductor but for it to remain normal without affecting the other subcables. The recovery heat flux for the single subcable case was about 15% larger than that for the case with all subcables normal.

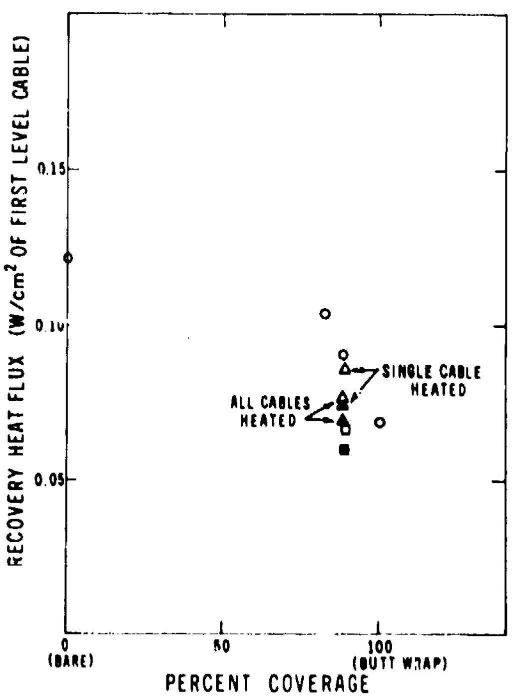

Fig. 5. Recovery heat flux per first level cable vs. percentage of tape coverage for different insulations and geometries. Open points - zero field; closed points - 2.8 T. Circles are for second level cable with perforated strip insulation and simulated BPA geometry; squares - same except Mylar tape insulation; triangles - final conductor with Mylar tape and realistic heat transfer geometry.

Results for perforated and unperforated insulation are consistent when plotted on the basis of total covered area.

Radial Fatigue Test

Mechanically, the weakest part of the conductor is the Mylar insulation. To control ac losses, it is important that shorts not develop between second subcables during the coil lifetime. The only significant cyclic load applied to the conductor is radial compression, that is, pressure normal to the wide face. Calculations show that the most highly stressed region is in the thirteenth turn at the axial midplane, with the stress depending on the transverse modulus of elasticity of the conductor. Calculated values range from 200 psi if $E = 1.3 \times 10^4$ psi to 420 psi if $E = 2 \times 10^5$ psi. The measured conductor modulus depends to a large extent on mechanical history, because there is a certain amount of "lost motion" in the as-fabricated material. Preliminary measurements indicate a value of $E \approx 2 \times 10^4$ psi, so that a test based on $E = 2 \times 10^5$ psi should be conservative. Cyclic loading at 4° K can be conducted at a rate of ~500,000 cycles per day, and it is necessary to use a larger load at 10^6 cycles to simulate the effect of 10^8 cycles. A study of existing data between 10^5 and 10^6 cycles for steel, copper, cloth-based-phenolic, and glass-based-epoxy indicates that a stress multiplier of 1.5 should conservatively cover the worst case. Therefore, it was decided to cycle the test sample between a maximum stress of $1.5 \times 420 = 630$ psi and a minimum stress of 2/3 this value.

The sample was a full-scale coil section, 4 turns high in the axial direction, 2 turns thick in the radial direction, and 4 in. long. Electrical leads, attached to all of the second subcables in seven out of eight conductors, were continuously monitored for inter-cable shorts as the sample underwent 1.1×10^6 stress cycles while immersed in liquid helium. No shorts were developed in this process and no damage was observed when the sample was disassembled.

Conclusions

The 5 kA conductor shown in Fig. 1 meets or exceeds all electrical and mechanical requirements for the 30-MJ coil. Stability tests show (a) small gaps in an otherwise thick insulating layer are very effective in ventilating a cabled conductor, (b) perforated tape is an equivalent method of providing open area, (c) the effects of support structure and tape insulation on recovery heat flux are not additive, and (d) it is possible to create a normal zone in a single second subcable without affecting neighboring subcables. There are still internal electrical and thermal phenomena in cabled conductors which need clarification.

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